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Method and device for fault detection in transformers or power lines

Technical Field of the Invention

This invention relates to a method and a device for improved
protection of power transformers, autotransformers or power
lines from the effects of internal faults by using an
10 advanced differential protection system.

Background of the invention

15 Faults in power transformers may lead to widespread conse-
quences, both in the form of power failure for a large group
of customers and in the form of that the faulty transformer
has to be exchanged or at least repaired. Both consequences
are troublesome and costly for the supplier of the
20 electrical power. The consequences of unwanted
disconnections of healthy equipment, such as power
transformers, is also very costly. In the worst case, the
unwanted disconnections can result in wider black-outs.

25 Protection devices such as differential relays normally
safeguard power transformers. Differential relays typically
have a minimum operating current level set to 30% of the
protected power transformer current rating. The set value
should be that high in order to prevent unwanted operation
30 of the differential relay due to the On Load Tap Changer
(OLTC) that typically is used in modern power transformers.
When OLTC moves from one position to another, amplitude

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mismatch between power transformer winding currents will outcome causing a false differential current. Normally, the range of an OLTC might be around 15% of rated voltage so the contribution of around 15% to differential current may

5   occur.

The set value should also be high enough in order to prevent unwanted operation of the differential relay due to Protection CT (current transformer) errors, or unequalities.

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Known transformer differential relays are usually not sensitive enough for low-level internal faults, which may happen for example within a power transformer tank. Power transformer winding turn-to-turn faults belong to such type

15   of internal faults. In the same time, according to available fault statistic, turn-to-turn faults are one of the most common internal faults inside a power transformer.

Traditional power transformer differential relays utilize

20   individual phase currents from different windings of the transformer in order to form the phase-vise differential currents. In modern numerical differential relayes these differential currents are usually formed by using mathematical equations, which are dependent on the vector

25   group of the power transformer.

The most common weaknesses of a traditional power transformer differential protection are long operation delays in case of heavy internal faults followed by main CT

30   saturation due to 2nd harmonic blocking feature, and unwanted operations for external faults. They also have bad sensitivity for low level internal faults, i.e. winding

turn-to-turn faults, which are thus allowed to develop into more severe faults, involving the power transformer iron core.

5   Long delays for heavy internal faults, they can be in the order of several tens of milliseconds, are a consequence of the harmonic distortion of the fault currents as they are seen by the differential relay. The harmonic distortion is due to initial heavy saturation of the current transformers
10 under fault condition. Harmonic restrain criterion prevents immediate operation of the differential protection.

Further, power transformer differential protections show a tendency to unwanted operations for faults external to the
15 protected zone with the power transformer, particularly for external earth faults.

Within this area of technology several inventions try to deal with these kinds of problems and some patents have been
20 granted.

As an example **US 5514978** is a patent that includes measureing of negative sequence impedance by using voltage measurements! The document describe an invention that
25 determins the existence of a turn fault that comprises estimating a current differential by dividing the negative sequence voltage phasor by a characteristic negative sequence impedance and subtracting the result from the negative sequence current phasor, and comparing the
30 estimated current differential with athreshold current differential.

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In the present invention measurements of the voltage is not
used at all. The present invention is instead based on
comparison of negative sequence currents from the diffrent
sides of the protected power transformer.

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The patent **US6507184** concerns a method and apparatus for
differential current measurement in a three-phase power
system. This invention is arranged to measure the
differential current between a first and a second terminal
10   and to obtain, for each phase, a measure of these currents.
This patent does not involve a negative sequence
differential protection at all.

The invention according to the patent **US6518767** concerns
15   protection of power transmission lines and includes tripping
of the circuit breaker. Similar circuitry is also used for
negative sequence current quantities, with the negative
secuence preselected values being set substantially lower to
produce a more sensitive response to possible faults in the
20   line.

The present invention concerns mainly the technical area of
power transformer protection, but can as well be extended as
power line protection or a combination of them, while the
25   above patent concerns protection of a power transmission
line only. The power transformer according to the present
invention introduces phase shift and voltage level
difference between power transformer sides. Therefore the
negative sequence currents from different power transformer
30   sides have to be first related to each other. After that the
negative sequence current differential principle or method
is used and a direction comparison is made to protect power

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transformers against internal short-circuit and ground
faults. Above this the present invention as well protect the
power transformer against turn-to-turn faults, which are
series faults and not a shunt fault as in the patent
5   application US6518767. This turn-to-turn fault protection
capability is an important advantage of the present
invention. This turn-to-turn fault is the most common, but
in the same time the most difficult, fault to detect within
a power transformer/autotransformer.

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The invention accordning to **US6483680** compares the phase
angle difference between fundamental frequency (i.e. 50Hz or
60Hz) and second harmonic component (i.e. 100Hz or 120Hz) of
the power transformer differential currents. More precisely,
15   the invention compare complex ratio between these two
phasors. This is done in order to determine if transformer
is faulty during energizing (i.e. switch-on) of power
transformer. This principle does not detect any internal or
external fault during normal operating condition (i.e.
20   through-load condition) of the power transformer, because it
can only operate during power transformer energizing from
one side. A typically power transformer is switched on just
a couple of times per year (i.e. often just once for the
yearly inspection). This means that the power transformer is
25   energized and connected on at least two side for most of its
life time (typically more than 95%). Therefore US 6483680
has very limited use during this short time of power
transformer energizing. Additionally this method typically
can not detect small faults like turn-to-turn faults even
30   during power transformer energizing.

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The patent application **WO02/33426** concerns a line
differential protection system for a power transmission
line. All three phase current values are obtained from both
the local end and the remote end of a power transmission
5   line. Comparison elements are aranged to compare the ratio
and angel values against preselected values, which establish
a restrain region in the current ratio plane. Current
values, which result in a ratio outside of the region,
result in a tripping of the circuit breaker. Similar
10   circutry is used for negative sequence current quantities,
with the negative sequence preselected values being set
substantially lower to produce a more sensitive response to
possible faults in the line.

15   This invention also concerns a differential protection
system for a power transmission line. The system is not
usable for a power transformer protection system.

20   **Summary of the invention**

The object of the present invention is to solve above
indicated problems and present a method and a device for
efficient detection of a fault in a power transformer.

25

Another object of the present invention is to detect if the
fault is internal or external.

A further object of the present invention is to detect if
30   the fault is symetrical or unsymetrical.

Still another object of the present invention is to present a method and a device that is able to detect turn-to-turn faults very fast and with high sensitivity.

5   These and other objects are achieved according to the present invention by a method as described in claim 1 and a device as described in claim 2 and a computer program product as described in claim 5.

10   The invention mainly compares the phase angle difference between negative sequence current component from different sides of power transformer. Negative sequence current quantities only exist during abnormal operating condition in the power system and they are of the fundamental frequency

15   nature (i.e. 50Hz or 60Hz). These negative sequence components from different sides have to be first put on the same base by matrix manipulations explained in the patent application. This is done in order to detect internal fault, including low-level winding turn-to-turn faults during

20   loaded condition of the power transformer. We use the same method as well to detect external fault condition (i.e. external/internal fault discriminator). However our principle can not detect internal fault during power transformer energizing from one side. In order for our

25   principle to work power transformer must be loaded and connected at least from two sides.

The real breakthrough in this method is the capability to detect low level internal faults like winding turn-to-turn faults, before then develop into the more serious earth faults, which are very much more time consuming and

5   expensive to repair.

Brief Description of Drawings

For better understanding of the present invention, reference

10   will be made to the below drawings/figures.

Figure 1 illustrates the connection of current transformers, defining the positive direction of currents.

15   **Figure 2** illustrates a protected zone that may include power lines and shows the default connection of some current transformers.

Figure 3 illustrates trajectories of the phasors

20   representing the contributions to the total negative sequence differential current from the power transformer primary (HV) and secondary (LV) sides, for an external earth fault on the HV side.

25   **Figure 4** illustrates in detail what is actually done by a matrix multiplication.

Detailed Description of Preferred Embodiments

30

In figure 1 is illustrated an internal/external fault discriminator for protection of power transformers. The

fault discriminator is made on pairs of components of the total negative sequence differential current. This discriminator may be implemented as a complement to the normal power transformer differential protection.

5

The internal / external fault discriminator determines the position of the source of the negative sequence fault currents with respect to the protected zone. If the source of the negative sequence fault currents is found to be

10   outside the protection zone, then the fault is external.

If the source is found to be inside the zone, the fault is internal. The position of the negative sequence current source is determined as follows. At an internal fault, a

15   degree of negative sequence differential current appears, and its two components (for a two-winding power transformer) are of the same direction, i.e. out of the protection zone.

At an external fault, the total negative sequence

20   differential current remains zero or is very small, until CT saturation sets in, while its two components are equal in magnitude, until CT saturation sets in, and of the opposite direction, i.e. one in, and the other out of the protection zone.

25

The internal / external fault discriminator can only be active when the protected power transformer is energized and loaded as well.

30   Both detection of faults, and a secure discrimination between internal and external faults can be achieved based on an analysis of the negative sequence differential

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current, or better, based on an analysis of its two (or
three at three-winding transformers) separate components, or
separate parts. With a reliable fault discrimination
algorithm, the power transformer differential protection

5   • operates very fast for heavy internal faults,

       • is stable against external faults,

       • operates for minor internal faults, as inter-turn.

Existence of a relatively high negative sequence current is

10   in itself a proof of a disturbance on the power system,
possibly a fault. The source of negative sequence current is
at fault. Thus, if the source of the negative sequence
current is found to be outside the protected zone, which
includes the power transformer, then the fault must be

15   external, and nothing shall be done in a short term. On the
other hand, if the source of the negative sequence current
is found to be inside the protection zone, then the fault is
internal, that is, a fault on the protected power
transformer can be suspected, and the transformer shall be

20   disconnected from the power system immediately. The
information on whether the fault is internal or external is
obtained within about one half of the fundamental power
system cycle after the fault has occured.

25   The principle of negative-sequence-current-based directional
criterion gives a fast and reliable discrimination between
external and internal faults. This is quite logical in the
case of unsymmetrical faults, where the negative sequence
currents are expected to exist. But the principle is just as

30   efficient at wholly symmetrical three-phase faults. The
reason is that when a symmetrical fault occurs, the negative
sequence system exists for a while, i.e. until the dc

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components in the fault currents vanish. This interval of
time is long enough for the directional criterion to
positively distinguish between an internal and an external
fault.

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In the following the principle of the discriminator is
discribed. In order to define what is meant by the "same
direction", and by the "opposite direction", an explanation
of this is as follows.

10

For an external fault, with the negative sequence source at
the point of fault, it is clear that the negative sequence
currents enter the healthy power transformer on one side,
and leave it on the other side, properly transformed.
15 According to Figure 1, the negative sequence currents on the
respective power transformer sides have opposite directions,
or better, the differential protection sees these currents
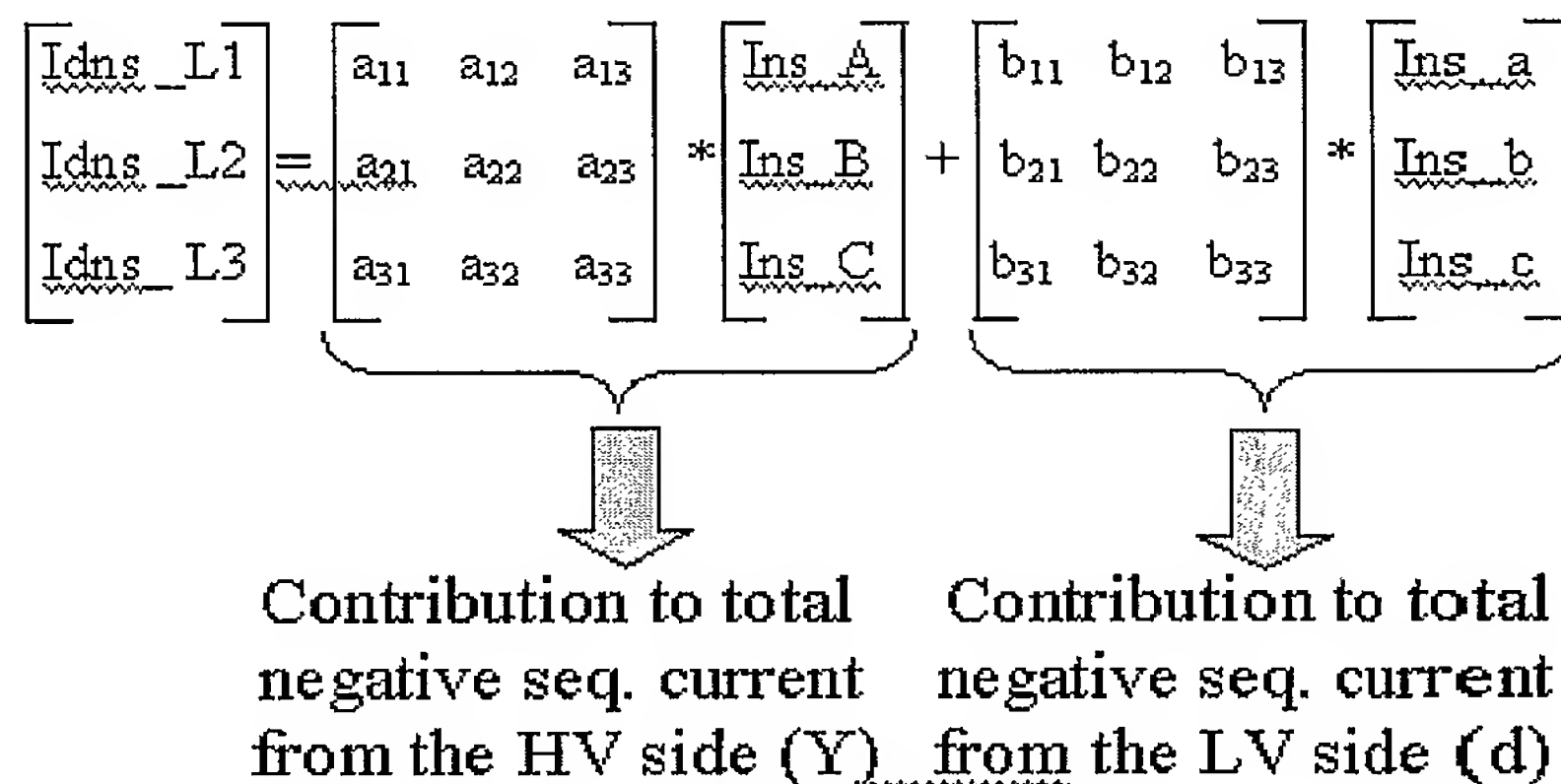with a relative phase shift of 180 degrees.

20 For an internal fault (with the negative sequence source at
the point of fault) it is clear that the negative sequence
currents leave the faulty power transformer on both sides.
According to Figure 1, the currents on the respective power
transformer sides have the same direction, the differential
25 protection sees these currents with a relative phase shift
of 0 degrees. In reality, there may be some phase shift
between these currents due to different negative sequence
impedance angles of the circuits on the respective power
transformer sides, while the magnitudes of the negative
30 sequence currents depend on the magnitudes of the negative
sequence impedances of circuits on the respective sides.

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The same coefficient matrices can be used for the calculation of the negative sequence differential currents as they are used for the calculation of the "common" power transaformer/autotransformer differential current. The only
5   difference is that the individual winding negative sequence currents must be fed into the equation instead of the individual winding phase currents. The coefficient matrices allow for power transformer ratio and vector group connection. Because the negative sequence differential
10 currents are symmetrical, only one differential current needs to be calculated, for example the negative sequence differential current in phase L1, i.e. Idns_L1. The negative sequence differential current must be calculated on a regular base and be available at any time.

15

$$\begin{bmatrix} Idns\_L1 \\ Idns\_L2 \\ Idns\_L3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} * \begin{bmatrix} Ins\_A \\ Ins\_B \\ Ins\_C \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} * \begin{bmatrix} Ins\_a \\ Ins\_b \\ Ins\_c \end{bmatrix}$$

20

Contribution to total   Contribution to total
negative seq. current   negative seq. current
from the HV side (Y)   from the LV side (d)

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The total negative sequence differential current Idns_L1 is low (theoretically zero) in case of an external fault, and high in case of an internal fault. More important, however, than the total negative sequence differential current
30 itself, are in this context its two (three for a three-winding power transformer) components, the one from the primary HV side, and one from the secondary LV side. These

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two components are compared as to their direction by the
fault discriminator, in order to decide whether the fault is
internal or external.

5 The two components of the total negative sequence
   differential current are phasors. Each of them has a
   magnitude and a phase in the complex plane. To be able to
   make a trustworthy directional comparison on these two
   phasors, each of their magnitudes must exceed a certain
10 minimum value. Otherwise, no directional comparison is
   allowed. The minimum value must be above values that can be
   measured during normal operation of the power system. This
   value is up to a couple of percent of the power transformer
   rated current.

15

   If both contributions to the total negative sequence
   differential current exceed the minimum value, which in
   itself can be taken as a sign that a fault must have
   happened, as the negative sequence currents are a
20 superimposed, a pure-fault quantity, then a directional
   comparison is made. The relative phase angle between both
   phasors, which represent the respective contributions, is
   determined. Based on the value of this relative phase angle,
   an internal or external fault is detected and declared.

25

   In **figure 2** is disclosed a protected zone that may include
   power lines. The figure also show the default connection of
   some current transformers. Analog to Digital converters are
   then connected to current transformers after which pre-
30 filters having a cutoff frequency of about 500 or 600 Hz are
   connected. To the pre-filters are connected Fourier filters
   in which the currents now are as phasors. Negative sequence

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currents occur on both sides. In order to be able to do any
relevant directional comparison, the negative sequence
currents from both sides of an eventual power transformers
must be referred to one (or the other) power transformer

5   side. The power transformer phase shift must be compensated
for. Negative sequence components from both side must exceed
a certain minimum value, otherwise no directional comparison
is made. The purpose of this condition is to exclude the
negative sequence currents due to eventual power system pre-

10   fault asymmetry. If the directional comparison results in an
indication of an internal fault, a trip command is issued.
The indication of an internal fault must prior to that be
confirmed several times.

Figure 3 illustrates the situation for an external single-

15   phase earth fault on the earthed Y side of an Yd1
transformer. There is little or no current transformer
saturation. At any point of time, the phase angle between
the two phasors was 180 degrees. The sum of these two
phasors, which is the total negative sequence differential

20   current, was nearly zero at all times, which corresponds to
the fact that the fault was external. Current transformers
were connected as in Figure 1.

Based on the phase angle between the two phasors, an

25   internal or an external fault is declared. An internal fault
is declared if the angle stays within ±60 degrees under an
interval of time.

In figure 4 it is in detail explained what is actually done

30   by the matrix multiplication. Negative sequence currents are
present on both sides. The negative sequence currents on
both sides of a power transformer are in a great majority of

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cases of different magnitudes, and of different phase
positions. In order to be able to do any comparison on these
currents, they must first be referred to a common base. This
is done by matrix multiplications in the next phase.

5

In order to be able to do any relevant directional
comparison, the negative sequence currents from both sides
of an eventual power transformer must be referred to one (or
the other) power transformer side. The power transformer
10   phase shift must be compensated for.

The negative sequence currents from both or all power
transformer sides are now referred to the same power
transformer side. Their magnitudes and phase positions can
15   now be correctly compared.

One of the most important factors to be taken into account
when forming a boundary is current transformer saturation
phenomenon.
20

Combined with some additional safety measures, such as time
constraints, the internal / external fault discriminator has
proved reliable. It takes normally about 10 ms after a fault
to detect the fault and classify it as internal or external.
25

The internal / external fault discriminator only works if
the protected power transformer is connected to some load,
so that currents can flow on both sides of the power
transformer, or at least two sides in case of a three-
30   winding power transformer. Thus, at an initial current
inrush, the algorithm declares neither internal, nor
external fault. In such cases one has to rely on the usual

features of the differential protection, such as, for
example, the harmonic restraint, or the waveform restraint
for inrush. Likewise, an internal fault on an energized, but
unloaded power transformer is not detected by the fault
5   discriminator.

As the newly introduced fault discriminator proved to be
very reliable, it has been given a great power. If, for
example, a fault has been detected, i.e. start signals set,
10   and it is found to be an internal one, then any eventual
block signals produced by either the harmonic or the
waveform restraints, are ignored. This assures the response
times of the protection below 20 ms, even for heavy internal
faults with severely saturated current transformers.

15

External faults happen ten to hundred times more often than
internal ones. Many differential protection relays have a
rather poor stability against external faults. If a fault
has been detected, and it is found to be an external one,
20   any trip request is cancelled. This assures high stability
against external faults. There is, however, an interesting
exception, which copes with minor internal faults, such as
inter-turn faults, which may occur due to, and immediately
after, an external fault. The idea behind this feature is as
25   follows.

If an external fault is being signalized without
interruption, while the zero sequence currents have been
eliminated from the fundamental frequency differential
30   currents (an option), and an eventual On-Load-Tap-Changer
(OLTC) movements compensated for, and then one or more start
signals are set, but at the same time no harmonic restrain

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signals (neither the external, nor the internal fault, caused current transformers to saturate), then a minor internal fault can be suspected. This minor internal fault can be prevented from developing into a major one by
5   immediate disconnection of the faulty power transformer, without waiting for the external fault to be cleared first.

Typically the operate-restrain characteristic of the differential protection must be set relatively high (for
10   example because of an uncompensated OLTC), then minor internal faults cannot be detected by electrical protections before they develop into major ones, with more severe damage to the power transformer as a consequence.

15   A special protection, based exclusively on the internal / external fault discriminator has been introduced, which is a completely independent part of the differential protection. This protection is called the Sensitive Negative Sequence Differential Protection (SNSDP) and has no logical
20   connection to the "usual" differential protection algorithm. No start signal has to be issued by the latter in order to activate the SNSDP.

The SNSDP is more sensitive than the "usual" differential
25   protection algorithm. Inter-turn faults including more than about 2 % of turns of a winding can be detected. An extra delay of 20 ms has been added as a precaution. Operate times of about 30 ms to 40 ms can be expected, which are better than the electromechanical Buchholtz relay's 50 ms to 150
30   ms.

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The principle of the internal / external fault discriminator
can be extended to power transformers with three windings.
If all three windings are connected to their respective
networks, then three directional comparisons can be done,

5   but only two comparisons are necessary in order to
positively determine the position of the fault with respect
to the protected zone. The directional comparisons, which
are possible, are: primary - secondary, primary - tertiary,
and secondary - tertiary. The rule applied by the internal /

10   external fault discriminator in case of three-winding power
transformers is,

- If all comparisons indicate an internal fault, then it is
  an internal fault.

- If any comparison indicates an external fault, then it is

15   an external fault

- If one of the windings is not connected, the algorithm
  automatically reduces to the two-winding version.
  Nevertheless, the whole power transformer is protected,
  inclusive the non-connected winding.

20

The negative-sequence-current-based directional principle
yields a fast and reliable discrimination between external
and internal faults. This is easy to understand in case of
unsymmetrical faults, where the negative sequence system is

25   expected to exist. But the principle is just as efficient in
case of wholly symmetrical faults. The reason is that when a
(symmetrical) three-phase fault occurs, the negative se-
quence current source appears at the fault for a while, more
exactly, until the dc components in the fault currents die

30   out. As far as power transformers are concerned, this inter-
val of time is long enough for the directional criterion to
declare either an internal or an external fault.

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The negative sequence quantities are used extensively in the field of relaying protection, particularly in the protection of power lines. The existence of relatively high negative sequence currents is in itself an indication of a distur-
bance, as the negative sequence currents are superimposed, pure-fault quantities. The negative sequence quantities seem to be particularly suitable for different kinds of directio-nal tests. One advantage of the negative sequence quanti-ties, as compared to the zero sequence ones, is that they are not stopped at a power transformer of the Yd, or Dy connection. Negative sequence quantities are properly transformed to the other side of any power transformer.

The protection principle of the present invention can easily be extended and applied for the protection of multi-winding power transformers as well as for the protection of autotransformers.

A method according to the invention may also, at least partly, be performed under control of a set of computer readable instructions or code means contained in a computer program storage device for making a computer or processor perform any of the steps of the above described method.

The invention may also use a computer readable product for carrying out the method according to the invention.

While the present invention has been described in terms of the preferred embodiments, the invention is not limited thereto, but can be embodied in various ways without departing from the principle of the invention as defined in the appended claims.

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